RESEARCH PROGRAM IN NUCLEAR AND SOLID STATE PHYSICS

VIRGINIA STATE COLLEGE

PETERSBURG, VIRGINIA 23803

SUPPORTED BY NASA GRANT NGR 47-014-006

ANNUAL REPORT

SEPTEMBER 1, 1973 - AUGUST 31, 1974

CAREY E. STRONACH

PROJECT DIRECTOR

SEPTEMBER 30, 1974

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This research project developed substantially during the 1973-74 year and has now matured to the point ehere it is enabling the involved parties to participate in contemporary physics research in an effective manner, and it is making substantial unique contributions to the training of young physicists at Virginia State College.

The grant year began with a series of setbacks. First, in the summer of 1973, the Kicksort analyzer then being used in the experiments was removed from the Space Radiation Effects Laboratory and returned to the agency at the Langley Research Center which had originally loaned it to SREL. Second, because of a shortage of personnel, the principal investigator was asked to teach an additional course at Virginia State College, thereby formally reducing his released time. Third, use of the SREL synchrocyclotron was pre-empted by another research group for the entire fall and early winter. However, all of these difficulties were overcome and the year was, on balance, highly successful.

The second problem actually provided the solution for the first. After receiving approval from NASA a line item change was made so that the portion of the released time salary of the principal investigator which was no longer needed was used to expand VSC's Northern Scientific 1024-channel analyzer to 4096 channels and add a digital stabilizer, a mixer/router, a processor interface, and a polaroid camera. These constitute a superb analysis system which should meet our basic needs for many years.

The third problem, no cyclotron time for the first five months, was balanced by generous time allocations in the late winter and spring of 1974. In fact, the

schedule which thus evolved was a blessing in disguise because the fall of 1973 was used to analyze data taken previously and to obtain the analysis system and prepare it for use.

Several VSC students participated in the research work. Ming-Chien J. Lin completed his master's degree work with his thesis "Positive Muon Precession in Iron", which is an analysis of data taken in a June, 1973 run. He also participated in other muon spin precession experiments. He is continuing to work on these in a doctoral research project at the College of William and Mary. Chandler M. Dennis, also a graduate student, began working on this project in April, 1974. He expects to complete his master's research on high energy positive pion interactions with nuclei this coming year. Two undergraduates, Daniel Epps and Gwendolyn Howell, also participated in the project. Their duties were primarily in data reduction. Daphne Clonts, a graduate student in science education, also participated in the experiments performed in June, 1974.

The VSC participation in these research projects would have been virtually impossible without the able leadership, expert assistance, and generous cooperation of Drs. William J. Kossler and Herbert O. Funsten of the College of William and Mary. Other non-VSC participants included Drs. B. J. Lieb and W. F. Lankford of George Mason University, H. S. Plendl of Florida State University, and M. L. G. Foy, presently with J. Sargent Reynolds Community College. Our non-VSC collaborators received no financial support from this grant.

PION -- NUCLEUS REACTIONS

The survey of negative pion absorption reactions on light and medium nuclei continued this past year, although no usable data were obtained until May. At that time a study of the π^- + ^{40}Ca absorption process was done. The data taken during that run are being analyzed and will be presented at the Nuclear Physics Divisional Meeting of the American Physical Society in Pittsburgh at the end of October. The

abstract of this paper is included as Appendix A to this report. The results indicate strong equivalent alpha emission and a strongly excited $7/2^-$ level in ^{37}Ar. Computer simulations of statistical nucleon evaporations (the Blann-Plaisil code) are being done and will be compared with the experimental data. Preliminary results indicate that a model in which the pion absorbs primarily on two nucleons which are then ejected with relatively high kinetic energy, leaving a relatively small (with respect to 140 mev) excitation energy in the (A - 2) nucleus, is not inconsistent with the data.

In late June the π^- + ^{23}Na absorption process was studied. This had been done in August, 1973, but equipment failures during the earlier run had resulted in data of marginal value. The recent data, which show much more structure than the 1973 results, are being analyzed, and the yield table should be complete very soon. The level schemes of nuclei in the A = 17 - 22 region are notoriously complex and this data reduction has consequently been complicated. One interesting feature of this spectrum is a very strong excitation of ^{18}O.

Pion absorption experiments with carbon and silicon targets were attempted in January, 1974, but electronics difficulties precluded successful data acquisition. The silicon experiment will be attempted again in late 1974.

In addition to the negative pion absorption experiments, two studies of positive pion reactions were done. In February the principal investigator collaborated with B. J. Lieb, H. S. Plendl, H. O. Funsten, and W. J. Kossler in studying the interaction of 220 mev π^+ with ^{16}O and ^{12}C. Lieb will present these results in Pittsburgh and the abstract is included here as Appendix B.

In early June the interaction of 90 mev π^+ with ^{16}O was studied, but the abnormally low beam intensity limited the spectrum statistics to marginal validity.

We expect to intensify our efforts in studying π^+ reactions, especially those produced by 220 mev pions from the Risk beam of the SREL cyclotron. Comparison of these data with the mirror nuclei state yields from the same target with

π^- beams should provide relevant information concerning isospin dependence of the π-Nucleus interaction.

We are currently planning to organize all of the π^- absorption data accumulated over the past three years into a paper to be submitted to one of the major physics journals. This should be completed in the autumn of 1974.

Because it reviews much of our work in this area to date, the talk presented by the project director to the Virginia Academy of Science in May, 1974, is included as Appendix C to this report.

MUON SPIN PRECESSION

During most of the year our muon spin precession work consisted of analysis of data taken with an iron target in May, 1973. This work constituted Ming-Chien J. Lin's master's thesis, which was included as Appendix B of our semi-annual report submitted in March, 1974. An abbreviated and corrected version of this analysis was presented by Mr. Lin to the Virginia Academy of Science in May, 1974. This is included as Appendix D to this report. An earlier preliminary analysis of these data was presented at the Nineteenth Annual Conference on Magnetism and Magnetic Materials held in Boston in November, 1973, by a former collaborator, Neil Heiman. This paper is included as Appendix E.

The VSC members of this research group participated in a series of muon precession experiments done at SREL in May, 1974. Targets included gadolinium, erbium, holmium, Fe_3Si, and single-crystal nickel. These data are currently in early stages of analysis. During the summer of 1974 plans were made for another series of muon spin precession experiments which were performed in September, 1974. These included an extensive survey of the precession properties of cobalt, and will be reported at a later date.

Although this field is in its infancy, much useful physics has been learned

from these experiments and more is anticipated. It is interesting to note that following publication of this group's original paper (Phys. Rev. Letters 30, 21, 1064 (1973)), a Soviet group repeated the experiments at Dubna, obtaining similar results.

EQUIPMENT

The major equipment obtained during the 1973-74 grant period was the analysis system mentioned in the introduction. The expanded 4096-channel analyzer and the digital stabilizer, mixer/router, and polaroid camera used with it have already provided many weeks of valuable service. Some difficulty has been experienced in utilizing the NS 441B computer interface and UNIBUS cable connection to the William and Mary PDP 11/10 computer, but this should be overcome in the very near future.

The other major equipment related expenditure was the redrifting of one of the Ge(Li) detectors in the SREL equipment pool. This was necessitated by the lack of a detector with acceptable energy resolution. The detector to which this was done was generally available to the group throughout the year and up to the present. Another redrifting will probably be necessary in another few months.

Two targets (calcium and cobalt) and several books constitute the only other equipment expenditures incurred.

A financial report on the year's operations is included as Appendix F.

TRAVEL

During the grant period the VSC participants made 46 round trips between VSC and the SREL cyclotron for the purpose of performing experiments. In addition, 39 round trips were made between VSC and William and Mary in order to confer with our collaborators and use the W & M IBM 360/50 computer. Two trips were made to the Langley Research Center to confer with our technical monitor, and one was made to the Richmond airport to pick up equipment.

The project director attended several professional meetings during the year. He attended the winter meeting of the American Physical Society in Chicago in early February, at which he presented a paper entitled "Nuclear De-excitation Gamma Rays Emitted Following Negative Pion Absorption on Sodium 23". A trip to Washington and the University of Maryland was made in late April in order to attend the spring meeting of the APS and a mini-conference on gamma rays coincident with pion-nucleus interactions. He also attended the Gordon Research Conference on Nuclear Structure Physics in New Hampshire in early July, at which he gave a talk entitled "Pion Absorption on Sulfur and Calcium", and also contracted Giardia Lamblia gastroenteritis from the local water supply.

Both the project director and graduate assistant Lin attended the annual meeting of the Virginia Academy of Science in Norfolk in early May. The two talks presented are, as noted earlier, in the appendix to this report.

FUTURE PROSPECTS

The acquisition of the Northern Scientific data analysis system this past year was a key factor in putting this program on a sound footing. In addition, the favorable report on the SREL synchrocyclotron given by the special committee on medium energy physics of the National Science Foundation has enhanced considerably the medium-term survival prospects of this accelerator. Student interest in the project, both among graduates and undergraduates, has increased, and there is no shortage of competent student workers. Relations with our collaborators at William and Mary, George Mason, and Florida State continue to be superb, with excellent prospects for long-term cooperation. Thus all aspects of the physical functioning of the program are most favorable.

The crux of the question of how we are to proceed in the future, however, relates, as it must, to the scientific merit of what we are doing. Here, in the project director's inherently biased view, prospects are also very positive.

The survey of negative pion absorption reactions has developed to the point where yield tables have been determined for a number of nuclei. Doppler broadening measurements are providing nucleon momentum distributions. The theoretical comparison with statistical evaporation processes, which is now underway, should provide a means of unfolding the pion absorption process in terms of the asymptotic processes of (1) impulse-approximation absorption on two nucleons which are immediately ejected with virtually no sharing of energy with the nucleons of the residual nucleus, and (2) sharing of the pion's rest energy by all the nucleons in the target nucleus and consequent nucleon evaporation. Reality appears to fall somewhere between the two extremes. Since this statistical evaporation program also calculates emitted nucleon energy spectra, results from these experiments could be used to calculate these spectra, which are of considerable practical importance in the area of cancer therapy utilizing pion beams. There is still much work to be done in completing this survey and making the above-mentioned theoretical comparisons.

The positive pion interaction experiments are still in their infancy, being about where the negative pion absorption experiments were two years ago. But with the techniques and experience gained from the earlier experiments rapid progress has been made. These experimental results are most useful in studying isospin dependence of pion-nucleus interactions and determining from this the nature of the interaction process. As of this writing two target nuclei have been studied, and, given the availability of the SREL Risk beam, approximately two years will be required to bring this survey up to the present level of the negative pion absorption work.

One fascinating future possibility would be a study of negative pion absorption on ^{18}O. Here charge conservation would prevent negative pion absorption on the outermost nucleons and the absorption would have to be upon an inner nucleon pair. The resultant yields should give precise information about the reaction process. Another possible set of experiments would look at charged particle emission in coin-

cidence with gamma rays. Although some work is being done along this line in the positive pion experiments at SREL, good statistics will require more intense pion beams, such as those at the new LAMPF, TRIUMPF, and SIN accelerators. Further in the future, if and when intense low-energy kaon beams come into existence, the study of kaon absorption processes by this technique could provide information on deep nuclear structure not anvailable by any other method.

The muon spin precession experiments have proven the technique to be an accurate, reliable, and unique method of determining internal magnetic fields in solids. Dependences on external applied fields, temperature, and crystal structure have been observed and explained. We expect to be able to apply this technique to a wide variety of materials, including ferromagnets, enhanced paramagnets, various alloys, crystals, and semiconductors. Various technological applications of the knowledge to be obtained are possible, including properties of alloys to be used in unique environments such as space, communications equipment, and exotic fuel storage.

During the next year our participation in this project is expected to concentrate upon very accurate temperature control and measurement in both high and low temperature cases. Long-range aspirations include study of esoteric materials, such as alloys, especially at very low temperatures, and precession behavior in very high external fields. Although when it is operating properly the SREL muon beam is quite adequate for targets of the size we have been using (about 2" x 2" and several grams thick), smaller targets are desirable in many cases because of uncertainties in field and temperature uniformity and the difficulties and expense incurred in obtaining macroscopic quantities of rare materials. Because of these factors more intense muon beams of smaller area and better energy resolution, such as that anticipated at the SIN cyclotron, appear attractive if this project develops appropriately in the future.

The acquisition of the Northern Scientific analysis system and the availability of the SREL equipment pool for experiments to be done there provide adequate equip-

ment for continuation of these experiments at their present level of sophistication indefinitely. Thus there is no urgent need for some critical piece of equipment like there was a year ago. To remain at the frontiers of research, however, will require innovation. In the pion-nucleus reaction field this should include such things as introduction of CAMAC electronics and a high-efficiency intrinsic germanium detector. The muon spin precession work would be enhanced by the presence of a superconducting magnet, a time digitizer, and CAMAC electronics. Some of these items may be obtained by our collaborators from other institutions, but we hope that future budgets will accommodate our share of the equipment needs.

Although we are parts of very competent experimental research teams, we have occasionally felt the absence of a theorist in our midst. One of the major future goals for this program should be, in my opinion, obtaining the services of a research associate, preferably a specialist in medium energy reaction theory. Such a person would be of enormous assistance to our group in data analysis and interpretation, and in developing ideas for future experiments.

In closing I wish to express the appreciation felt by all the members of our research groups for the support provided by NASA. It has made all of the research participation described in this report possible and has been of immeasurable value in developing our physics department. We hope with confidence that the results of this research will be of lasting scientific value.

Respectfully submitted,

Carey E. Stronach
Project Director

September 30, 1974

Physical Review
Analytic Subject Index
Number <u>53.4</u>

Bulletin Subject Heading
in which Paper should be placed
<u>Medium Energy Nuclear Reactions</u>

<u>Nuclear De-excitation γ Rays Following π^- Capture on ^{40}Ca.</u>[†] C. E. STRONACH and C. M. DENNIS, <u>Virginia State College</u>; W. J. KOSSLER and H. O. FUNSTEN, <u>College of William and Mary</u>; W. F. LANKFORD and B. J. LIEB, <u>George Mason University</u>-- π^- from the SREL synchrocyclotron[1] were stopped in a ^{40}Ca target. Prompt γ rays were observed with a Ge(Li) detector. Daughter nuclei seen, with their % yields, include ^{39}Ar(4.7), ^{38}K(1.5), ^{38}Ar(1.5), ^{38}Cl(.34), ^{37}Ar(2.1), ^{37}Cl(1.8), ^{36}Ar(5.2), ^{34}S (1.2), ^{34}S(1.9), ^{29}Si(.67), ^{28}Si(2.1), ^{26}Mg(.61), ^{24}Mg(2.7), and ^{20}Ne(2.4). Odd-even daughter nuclei were primarily in $7/2^-$ states. Comparisons with statistical evaporation calculations will be given.

Submitted by

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Physical Review
Analytic Subject Index
Number 53.4

Bulletin Subject Heading
in which Paper should be placed
Medium Energy Nuclear Reactions

Single Nucleon Removal Cross Section Ratios in π^+ Reactions on ^{16}O Near the (3,3) Resonance.$^+$ B. J. LIEB, George Mason U.; H. S. PLEIDL, Florida State U.; H. O. FUNSTEN and W. J. KOSSLER, College of William and Mary; and C. E. STRONACH, Virginia State College-- A H_2O target was bombarded with 190 MeV π^+ from the SREL^1 synchrocyclotron. Prompt γ rays were detected by a 40 cm^3 Ge(Li) detector in coincidence with the incoming π^+. De-excitation γ rays from residual states of ^{16}O, ^{15}O, ^{15}N, ^{14}N, ^{14}C, ^{13}C and ^{12}C were identified and cross sections determined. The cross section ratio for $^{16}O(\pi^+,\pi^+n+\pi^+,\pi^0p)^{15}O$ to $^{16}O(\pi^+,\pi^+p)^{15}N$ leading to the first 3/2⁻ mirror states is .57±.12. The previously determined ratio for $^{16}O(\pi^-,\pi^-n)^{15}O$ to $^{16}O(\pi^-,\pi^-p+\pi^-,\pi^0n)^{15}N$ leading to the same levels for 230 MeV π^- is 1.7±.4. The ratios expected from the impulse approximation are 1/3 and 3 respectively.

Submitted by

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Please do not schedule on Thursday, 31 October 1974.

ASTRONOMY, MATHEMATICS, AND PHYSICS

PION ABSORPTION ON LIGHT AND MEDIUM NUCLEI.

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Petersburg, Va. 23803, W. J. Kossler* and H. O.
Funsten, Dept. of Physics, Col. of William and
Mary, Williamsburg, Va. 23185, and W. F. Lankford,
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23030

Analysis of the prompt gamma ray spectrum produced by stopping negative pions from the SREL[1] synchrocyclotron on ^{23}Na indicates approximately equal fractions of one, two, three, and four nucleon emission processes plus a smaller fraction of six nucleon emission processes.

The prompt gamma spectrum from stopping of negative pions on ^{32}S indicates relatively strong emission of one, two, and three alpha particles, similar to an effect observed in fast pion reactions[2]. (Aided by NASA grant NGR 47-014-006)

Carey E. Stronach

PION ABSORPTION ON LIGHT AND MEDIUM NUCLEI

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Co-authors: W. J. Kossler
            H. O. Funsten
            W. F. Lankford

We have studied the process of negative pion absorption on a number of light and medium mass nuclei using the pion beams from the Space Radiation Effects Laboratory in Newport News, Virginia. Today I wish to present these results and compare them with results obtained by others in similar experiments.

An impulse approximation model of the pion absorption process implies that the pion will absorb almost exclusively on nucleon pairs, single nucleon absorption being suppressed by energy and momentum conservation requirements. We have observed gamma rays from nuclei which could be produced by the two-nucleon process, and have also observed excited daughter states corresponding to 1, 3, 4, and occasionally more nucleons emitted. These results may or may not arise from absorption on nucleon pairs.

The first figure shows the physical geometry of our experiment. The incoming negative pions passed first through slabs of aluminum and borated paraffin to reduce their energies so that our target would be sufficient to stop them. Then they passed through two scintillation paddles before stopping in the target. Another paddle was placed behind the target. A logical $12\bar{3}$ represented a pion stop. Gamma rays were observed with a 40 cm^3 lithium-drifted germanium detector which was placed adjacent to the target just outside the beam path. The $12\bar{3}$ signals constituted the START input of a time-to-amplitude converter, and gamma pulses from the germanium detector, after passing through a constant fraction discriminator, constituted the STOP input to the time-to-amplitude converter. The second figure shows the electronic flow chart.

The third figure is a typical timing curve obtained by putting the time-to-amplitude converter output into a multichannel analyzer. The prompt peak and another section far from it were used to gate and route our energy analyzer in two memory groups. A pulser was used for digital gain stabilization.

The fourth figure lists the excited daughter states observed in the prompt spectrum from negative pion absorption on sulfur 32. The fifth figure shows these data in histogram form. We note that 2-, 3-, and 4-particle emissions occur with approxi-

mately equal strength and the 5- and 7-particle emissions are much weaker, but also note that 6-, 8-, and 12-particle emission do not fall off nearly as rapidly. It is possible, but by no means certain, that these effects arise from pion absorption on alpha particle clusters in nuclei, further suggesting this particular form of short-range correlations among nucleons. On the other hand, this effect could also arise from a statistical evaporation process after the nucleus has absorbed the 140 mev rest energy of a pion, with alpha removal being energetically favored because of its very large binding energy. The corresponding Q values are given in the sixth figure. One argument in favor of the alpha absorption process is that we see daughter states corresponding to simple alpha removal from the target nuclei, not alpha removal from nuclei which have already absorbed the negative charge of the pion. Again, however, it must be noted that even-even daughter nuclei are energetically prefered and are also easy to observe because they all have characteristic $2^+ \rightarrow 0^+$ gamma rays which are seen in cascade from all higher levels. Thus this question is far from settled and much more work, both experimental and theoretical, must be done.

The seventh figure lists the states observed in coincidence with the stopping of negative pions on sodium 23. Figure eight gives these data in histogram form. Sodium 23 is the only odd-even nucleus we have studied, and we note that 1-, 2-, 3-, and 4-particle emission were seen with approximately equal strength, which is quite different from the even-even sulfur 32 case. We were unable to look for 7-particle emission because the first excited state of oxygen 16 was beyond the limit of our energy range.

Figure nine lists the results of an earlier study of negative pion absorption on carbon 12. The only states observed, other than those resulting from feeding, were the 717 kev 1^+, 0 state and the 2154 kev 1^+, 0 state of boron 10. The 1740 kev 0^+, 1 state of boron 10 was not excited. This is analogous to the observation of Kossler and Funsten that the 2311 kev 0^+, 1 state of nitrogen 14 is only very weakly excited by pion absorption on oxygen 16.

The results of that experiment on oxygen 16, along with the results obtained by the Lewis-Engelhardt-Boschitz group at CERN in a similar experiment, are given in figure ten. Again we note 1-, 2-, 3-, and 4-particle emission. The CERN group has also studied pion absorption on fluorine 19 and phosphorus 31. In each case 1-, 2-, 3-, 4-, and 5-particle emission were observed.

The negative pion absorption process introduces 140 mev of energy into the nucleus with virtually no momentum transfer. Thus if the absorption is on, say, two nucleons which are emitted without any strong final-state interaction with the daughter nucleus, the momentum distribution of such pairs should be very nearly the same as the momentum distribution they had before pion absorption. Momentum conservation would give the daughter nuclei equal and opposite momentum, and thus any gamma rays emitted before the nuclei could slow down would display a Doppler broadening. This broadening can be measured and the pair-momentum distribution thus computed. Figures eleven and twelve show this computation based upon data taken from pion absorption on nitrogen 14 and comparison with earlier data taken by Kossler and Funsten on oxygen 16. The width of the 4433 kev line of the daughter nucleus carbon 12 implies that the $1p1/2$ nucleons in nitrogen 14 have an average pair-momentum of 168 mev/c. When this value is folded into the rms nuclear radius of nitrogen 14 from Elton's book <u>Nuclear Sizes</u>, an average $\overline{KR}$ product of 2.12 is obtained, thus verifying the Heisenberg uncertainty principle, which is reassuring.

In summary, noting figure thirteen, we can make the following statements about pion absorption on light and medium nuclei:

1) The more strongly excited daughter states give yields of 4 to 6%.

2) For a given target we observe gamma rays corresponding to 10 to 30% of the absorbed pions. We must remember that this technique does not permit observation of ground-state transitions.

3) In addition to daughter states corresponding to the expected two-nucleon emission, states resulting from multi-nucleon emission are seen with yields of similar mag-

nitudes. These states resulting from multiple-nucleon emission processes are seen more frequently in the medium mass range than they are for very light target nuclei.
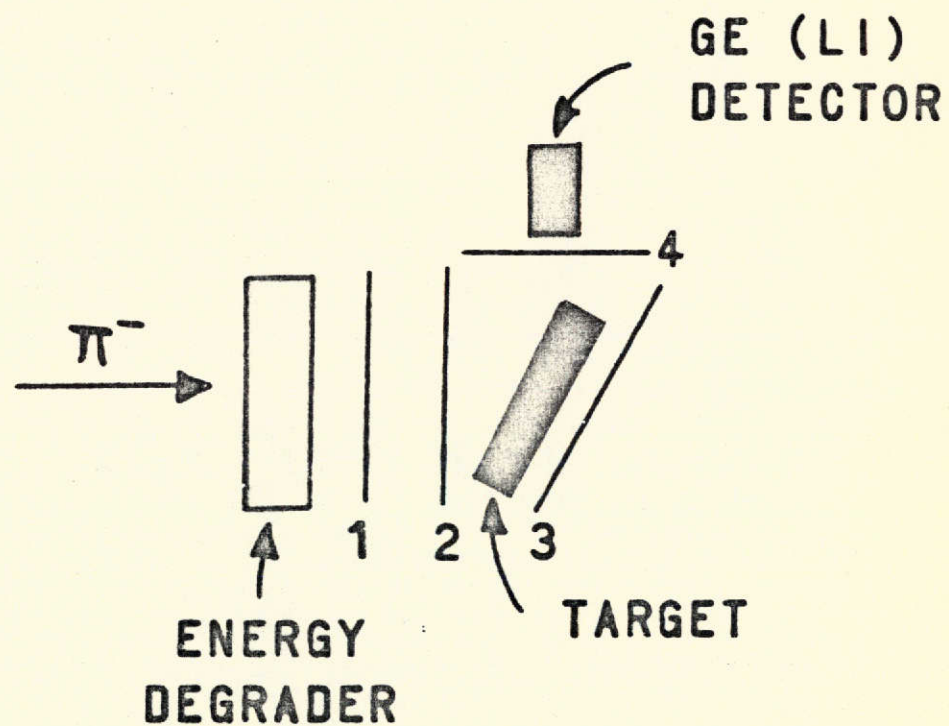
4) We see some evidence of absorption on alpha particle groups. This could result from statistical evaporation processes, however, and is not conclusive.

5) One-nucleon emission is found to be relatively stronger in odd-even nuclei than in even-even nuclei.

We are continuing these experiments and are presently studying negative pion absorption on calcium 40. Earlier this year we bombarded oxygen 16 with 220 mev positive pions. These data are currently being analyzed.

Thank you!

PION ABSORPTION APPARATUS

GE (LI)
DETECTOR

π^-

ENERGY
DEGRADER

1   2   3

4

TARGET

NOTES

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

GATE

LSD

ON

ENERGY
ANALYZER

ROUTER

1

AND

OFF
LSD

12

2

PRINTER
& SCOPE

ON
LSD

3

ANTI

TIME
ANALYZER

123

ON
TSCA

4

ANTI

123I
SLOW
AMP

OFF
TSCA

CFD

OR

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γ

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AMP

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NOTES

PROMPT

PEAK

NO. EVENTS

ON-TIME

OFF-TIME

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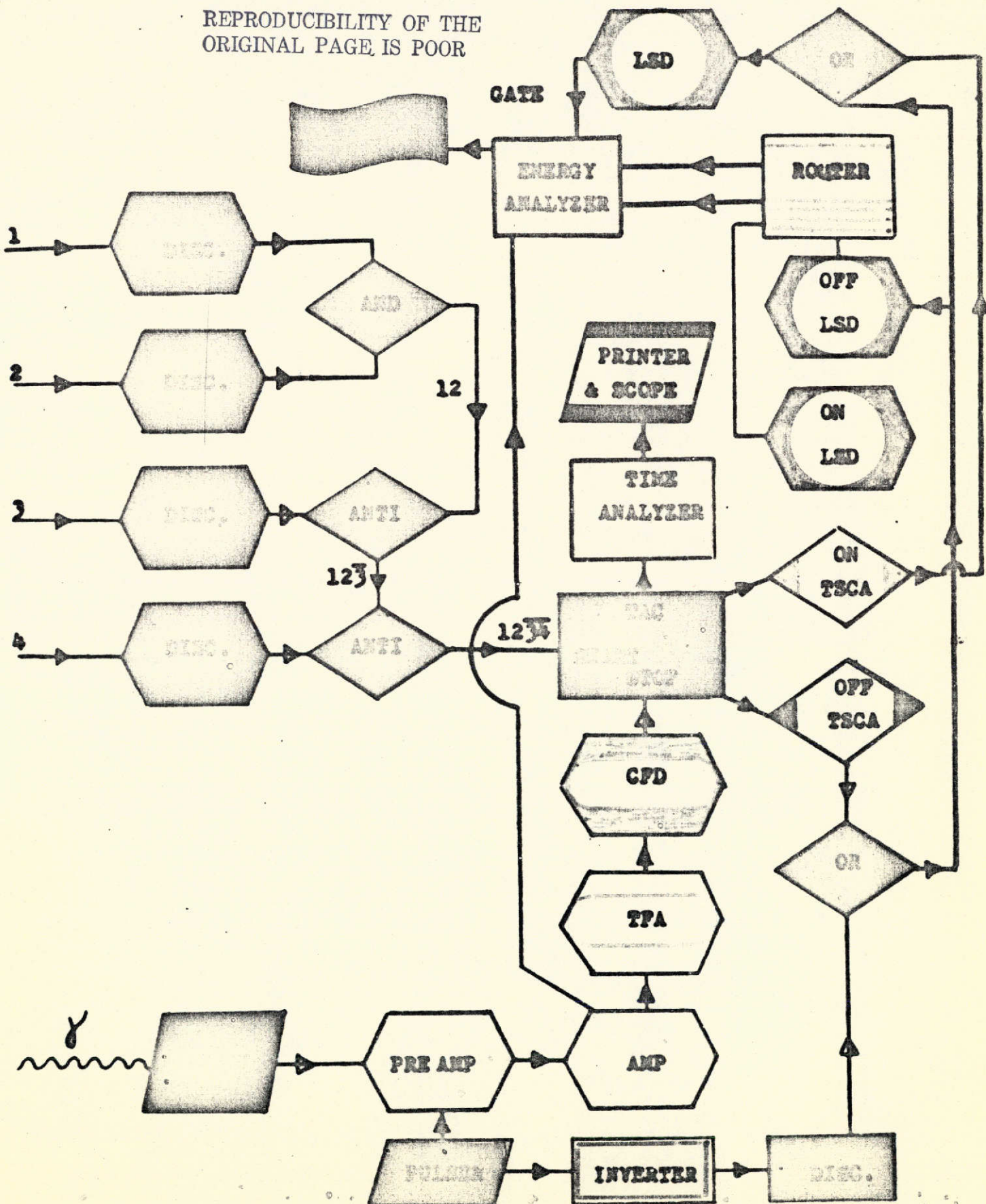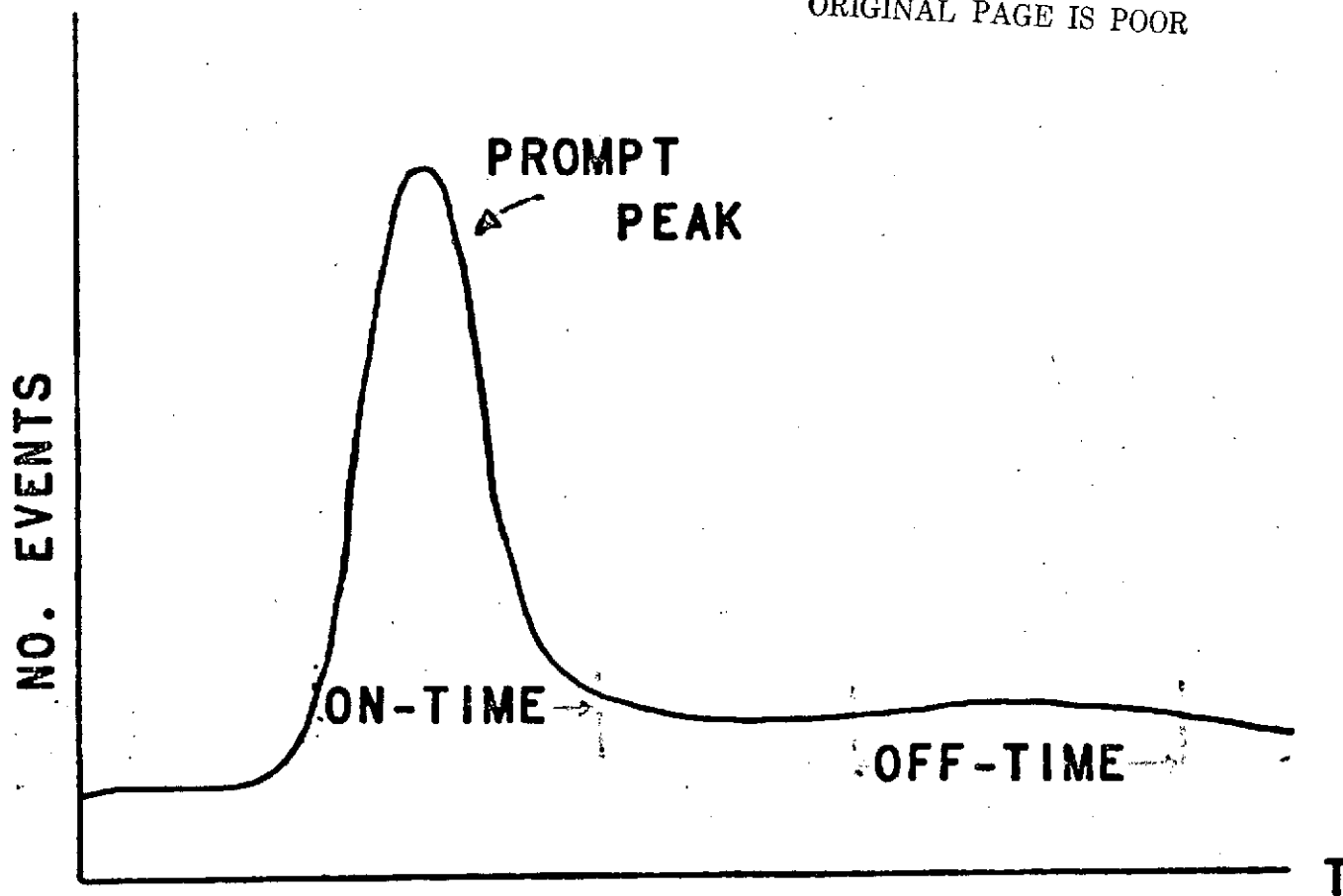
TYPICAL TIMING SPECTRUM

NOTES

$$\pi^- + {}^{32}S$$

DAUGHTER STATE		ENERGY (KEV)	YIELD (%)
${}^{31}P$	$5/2^+$	3295	2.04
${}^{31}Si$	$1/2^+$	752	.30
${}^{30}P$	$0^+, 1$	678	.25
${}^{30}P$	1^+	709	.14
${}^{30}P$	2^+	1455	.56
${}^{30}Si$	2^+	2235	5.65
${}^{29}Si$	$3/2^+$	1273	3.86
${}^{29}Si$	$5/2^+$	2032	.57
${}^{29}Si$	$7/2^-$	3623	1.50
${}^{28}Si$	2^+	1779	6.07
${}^{27}Al$	$3/2^+$	1013	1.28
${}^{27}Al$	$5/2^+$	2732	1.52
${}^{26}Mg$	2^+	1809	3.45
${}^{26}Mg$	2^+	2938	.55
${}^{25}Al$ $7/2^+$ or ${}^{25}Mg$	$7/2^+$	1610	.41
${}^{25}Mg$	$1/2^+$	586	.47
${}^{24}Mg$	2^+	1369	2.21
${}^{20}Ne$	2^+	1633	1.76
			Sum= 32.6%

$$\pi^- + {}^{32}S$$

REPRODUCIBILITY OF THE
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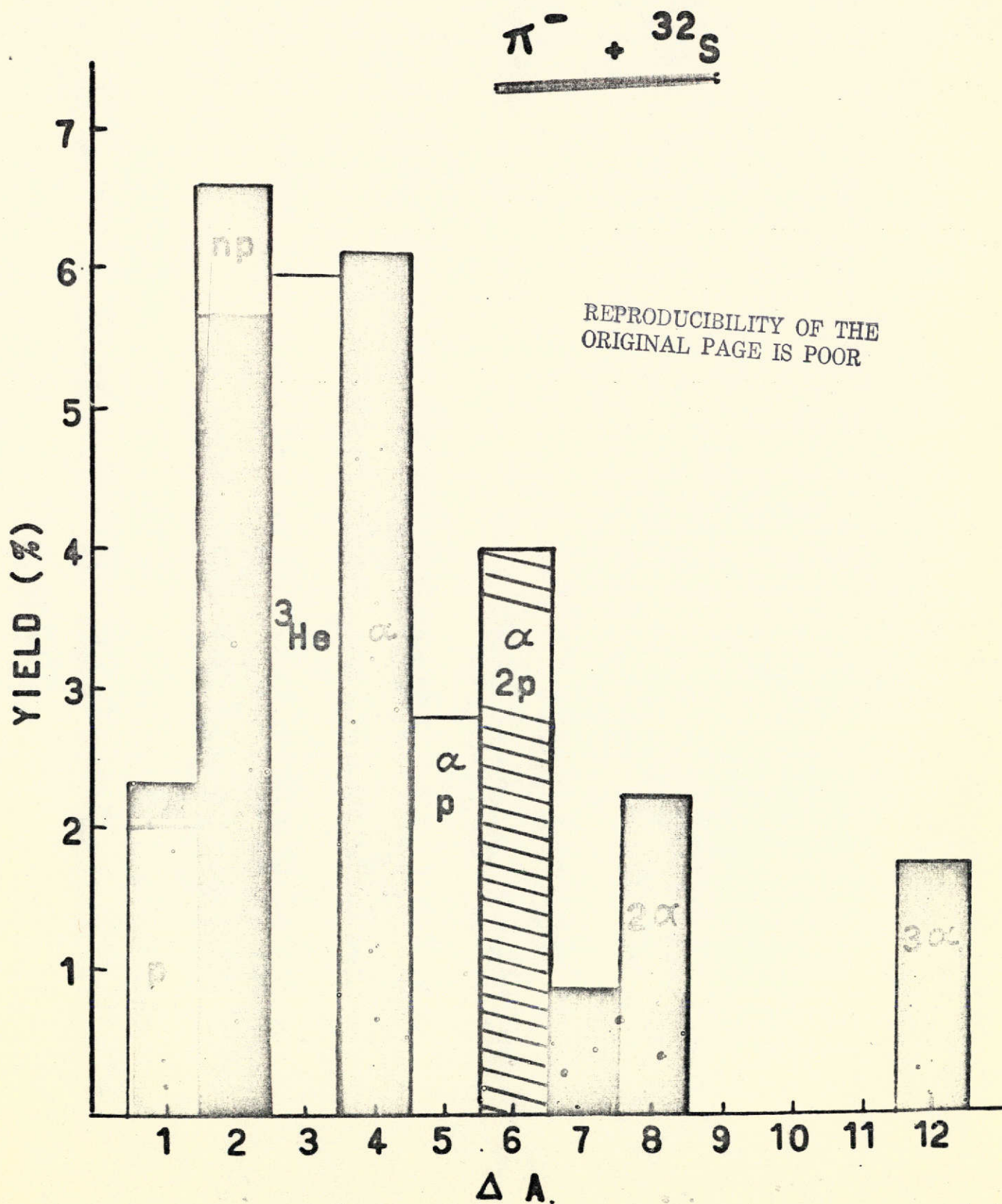
Q Values for products of the $\pi^- + {}^{32}S$ reactions

$$\pi^- + {}^{23}\text{Na}$$
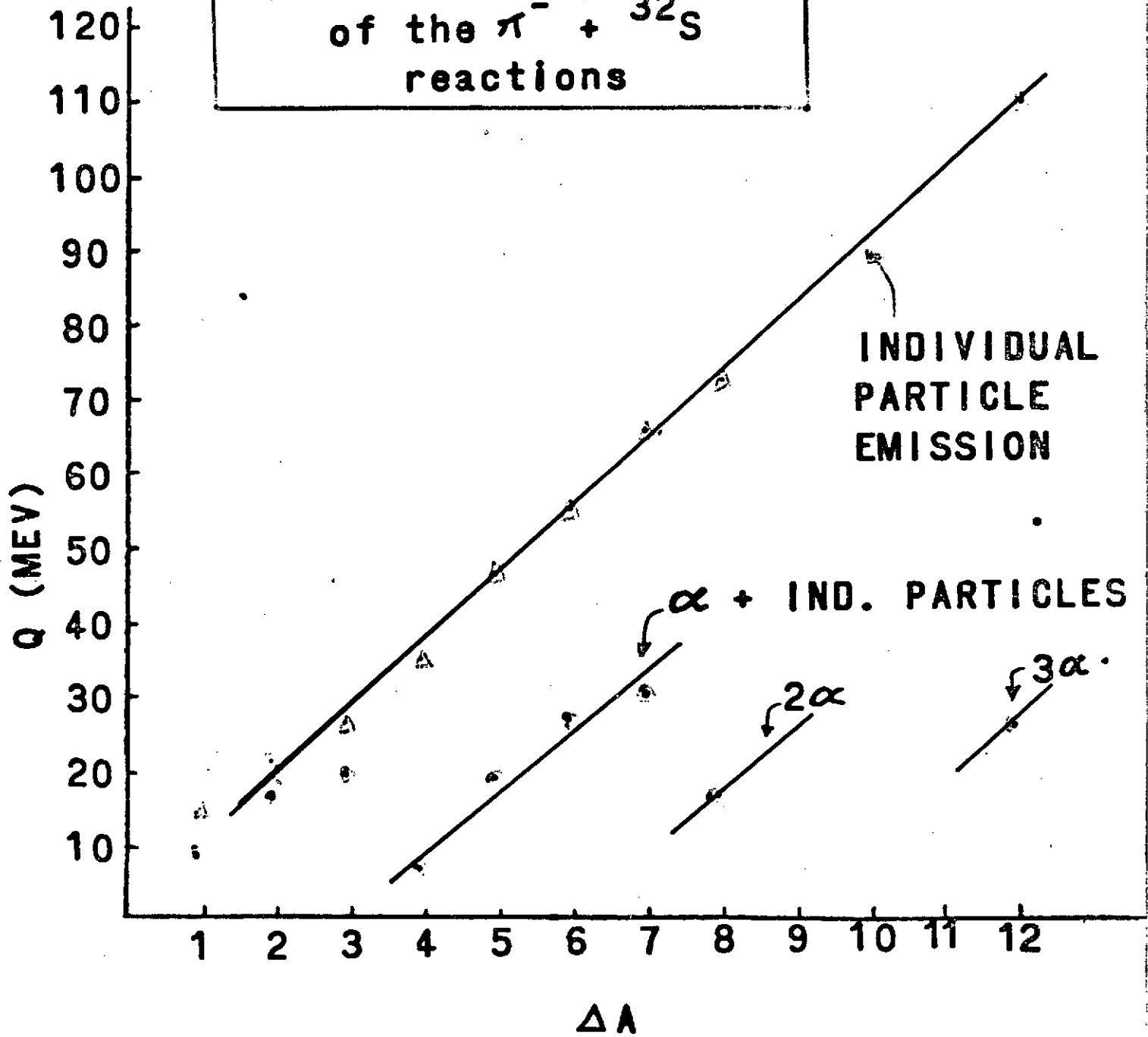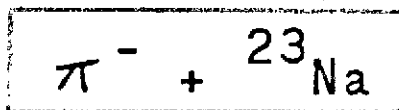
Daughter State	Energy (KEV)	YIELD (%)
$^{22}\text{Ne} \quad 2^+$	1275	3.7
$^{21}\text{Ne} \quad 7/2^+$	1403	3.7
$^{20}\text{Ne} \quad 2^+$	1633	4.2
$^{19}\text{F} \quad 3/2^+$	1350	4.1
$^{17}\text{O} \quad 1/2^+$	871	1.6
$^{17}\text{O} \quad 1/2^-$	2195	weak

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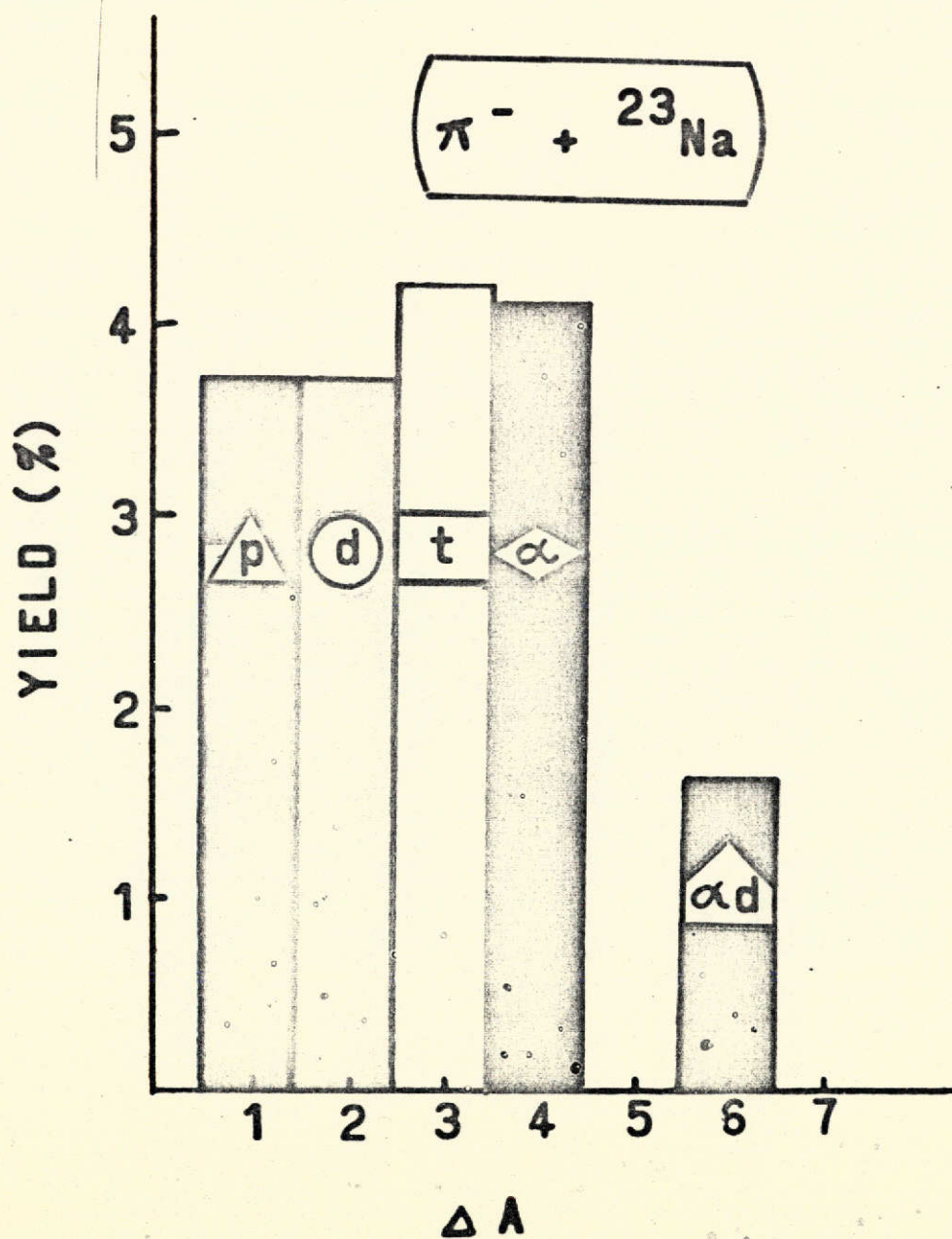
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Daughter State	J^π, T	Yield
^{10}B, 717 keV	1^+, 0	9.99%
^{10}B, 2154 keV	1^+, 0	2.75%
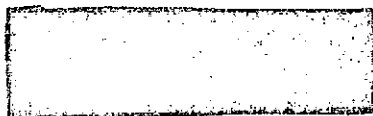
Isotope	E_γ (KeV)	N_γ/N_π (%) Lewis	Kossler
N^{14}	1632	1.79	1.79
N^{14}	2311	1.81	2.24
C^{13}	3684	0.45	0.69
C^{13}	3854	0.35	0.25
C^{12}	4440	3.10	0.84
N^{14}	5106	0.25	0.15
N^{15}	5270	0.29	0.15
C^{14}	6727	-	0.032

NOTES

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MOMENTUM DISTRIBUTIONS
OF NUCLEON PAIRS

$$\Delta E = E_\gamma \frac{V}{C} \cos \theta$$

$$\frac{\Delta E_{FWHM}}{2 E_\gamma} = \frac{\overline{V}}{C}$$

$$\pi^- \text{ on } {}^{14}N \longrightarrow {}^{12}C^*$$

$$^{12}C^* \longrightarrow {}^{12}C + 4433 \text{ KeV } \gamma$$
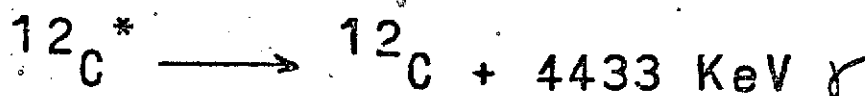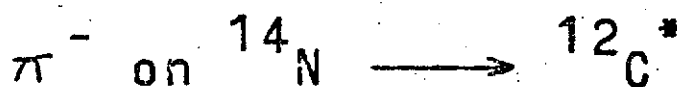
$$\frac{\Delta E_{FWHM}}{2} = 66 \text{ KeV}$$

$$\therefore \frac{\overline{V}}{C} = \frac{66}{4433} = 1.5 \times 10^{-2}$$

$$\overline{p} = m\overline{v} = 12 \times 931 \times 1.5 \times 10^{-2}$$

$$\overline{p} = 168 \pm 6 \text{ MeV/c}$$

$$\overline{K} = (0.855 \pm 0.029) \text{ fm}^{-1}$$

$$\pi^- \; {}^{16}O \longrightarrow {}^{14}N$$
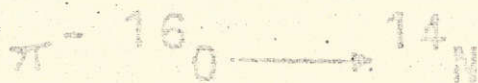
$$\bar{p} = 145 \; \text{MeV/c} \; , \; \bar{K} = 0.733 \; \text{fm}^{-1}$$

$$R_{RMS}({}^{16}O) = 2.65 \; \text{fm} \quad (\text{Elton})$$

$$\therefore \bar{K}R = 1.96$$

$$\pi^- \; {}^{14}N \longrightarrow {}^{12}C$$
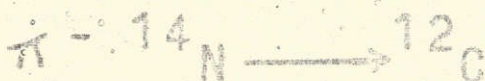
$$\bar{p} = 168 \pm 6 \; \text{MeV/c}$$

$$\bar{K} = (0.855 \pm 0.029) \; \text{fm}^{-1}$$

$$R_{RMS}({}^{14}N) = 2.48 \; \text{fm} \quad (\text{Elton})$$

$$\therefore \bar{K}R = 2.12 \pm .07$$

NOTES

SUMMARY

1. Strongly excited states yield
   $\sim 4 - 6 \%$.

2. $\sim 10 - 30 \%$ of stopped pions
   produce nuclear γ's.

3. Yields for multinucleon emissions
   $(\Delta A > 2)$ comparable to $\Delta A = 2$ yields
   for medium mass nuclei.

4. Some evidence of absorption on
   α particle groups. Not conclusive.

5. One-Particle emission relatively
   stronger in odd-even nuclei than
   in even-even nuclei.

NOTES

PRECESSION OF POSITIVE MUONS IN IRON. M. J. Lin*
and C. E. Stronach, Dept. of Physics, Va. State
Col., Petersburg, Va. 23803, M. L. G. Foy and
W. J. Kossler*, Dept. of Physics, Col. of William
and Mary, Williamsburg, Va. 23185, and N. Heiman,
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Polarized positive muons from the SREL[1] syn-
chrocyclotron were stopped in Fe. The magnetic
fields at the muon sites were determined from the
precession of the angular distribution of the
decay positrons. The same data yield the initial
polarization and the decay time constant of the
slow depolarization. The temperature was varied
from 298K to 1073K so that the shift from the
ferromagnetic to the paramagnetic state was obser-
ved. The internal field was approximately 3600
gauss and variations in the depolarization time
constant were observed which can be explained in
terms of magnetization fluctuations at the stop-
ping sites. (Aided by NASA grant NGR 47-014-006)

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PRECESSION OF POSITIVE MUONS IN IRON

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N. Heiman

Polarized positive muons from the Space Radiation Effects Laboratory synchro-cyclotron were implanted in targets of iron and nickel. For measurements on both paramagnetic and ferromagnetic iron, the external magnetic field was supplied by a large C-type electromagnet carrying a current of about 100 amperes.

The positive muon is an excellent probe for studying properties of solids in magnetic fields. Its lifetime is about 2.2 microseconds, long enough for easy timing, short enough for high count.rates. The positive muon decays into a positron and two neutrinos and the positron can be easily detected. The first picture shows production of positive muons from pion decay. The second picture depicts the precession of a muon in a magnetic field. The third picture shows the muon decay process. The positron is most likely to be emitted in the direction of the muon's magnetic moment, which is known to 3 parts per million. The muon precesses in a magnetic field and the precession frequency gives a direct, high precision measure of the field intensity. The angular distribution of positrons from polarized muons is anisotropic by about 30% and precesses with the muon's precession, the form of the data being similar to that of time differential perturbed angular correlations.

Implanted muons cause minimal radiation damage. One can have infinitesimal con-centrations and no residual contamination. The impurity effects are much like those from hydrogen. There are minimal structure effects to be considered and no nuclear or quadrupole effects.

Figure 1 indicates that the ellipsoidal target, 3" in diameter and 1/2" long, of iron was placed in an insulated furnace, whose heating coils were connected to a Marshall temperature controller which monitored the temperature by a thermocouple. Scintillation paddles 1 and 2 were in front of the target, 3 behind, 4 and 5 at angles as shown in the figure. Figure 2 is a schematic of the electronics. A muon which stopped in the target would traverse scintillation paddles 1 and 2 but not 3. A signal for a stopped muon, a $12\bar{3}$ (meaning a logical AND between counters 1 and 2 with a logical ANTI between the 12 pulse and counter 3), as shown in figure 2, was

used to start a time-to-amplitude converter or TAC.

A decay positron signal, either a $4\bar{1}$ or a $5\bar{1}$, stopped the TAC (The $\bar{1}$ anticoincidence requirement ensured that the signals in 4 and 5 were not due to particles from the incident beam.). The output of the TAC was fed to two multichannel pulse-height analyzers. A Northern Scientific 1024-channel analyzer and part of a Kicksort 4096-channel analyzer were used to accumulate the data from the outputs of the TACs. Data were recorded with a teletype. Data were fitted into equation 1, which gives the number of decay positrons as a function of time after muon stops. The precession frequency of the angular distribution of the decay positrons was measured in order to determine the magnetic fields at the sites of the muons (B_μ). The same data yielded the initial polarization (P) of the stopped muons and the time constant (τ_R) of the slow depolarization. Data were collected as a function of temperature from room temperature to 1073°K so that the shift from the ferromagnetic to the paramagnetic state in iron was observed.

Figures 3 and 4 are two examples of data for paramagnetic iron (at 1073°K) and ferromagnetic iron (at 873°K). Each set of data is the result of approximately two hours of counting.

Only one run was performed in the paramagnetic iron region. Here B_μ = 1530 gauss. It is very interesting that the magnetic field at the muon sites is approximately equal to the external field. The initial polarization P was equal to 40% of P_{Cu}, the initial polarization observed in a copper target of similar dimensions, as seen in figure 8. The depolarization time constant τ_R was 0.25 microseconds, as shown in figure 9. The precession frequency was 20.5 megacycles.

In the ferromagnetic iron region the magnetic field at the muon sites was fitted to a Brillouin function, as shown in figure 5, with a saturation field of 3600 gauss. The circular data points were taken with a current of 100 amperes in the electromagnet. In the temperature range from room temperature to 1023°K, B_μ decreased from approx-

imately 3600 gauss to 1580 gauss (see figure 5).

The results for the initial polarization in terms of the polarization in copper, P_{Cu}, for each run are given in table 1. The ratio of the polarization in iron to that in copper increases from about 40% at 298°K to near 70% as the Curie temperature is approached (see figure 8). It is believed thst this is due to domain alignment. A muon will not precess if it stops in a domain where the magnetization or internal field is in the same direction as the muon's polarization. The amplitude of the precession signal thus depends upon the degree to which the domains are aligned transverse to the muon polarization.

The solid line in figure 8 is a measure of this domain alignment extracted by dividing the measured permeability by the magnetization and normalizing to the initial polarization of the muons in the iron target. In figure 9 the depolarization time constant τ was of the order of 0.25 microsecond and increased slightly with temperature up to about 900°K and then dropped sharply as the temperature approached the Curie point. It then increased sharply as the temperature increased. This indicates that the relaxation was dominated by the static inhomogeneity up to 900°K, at which point magnetization fluctuation became very important. The dashed line in figure 9 illustrates this trend. Varying the magnetic field at the muon sites, B_{μ}, by changing the temperature or varying the external field seemed to have little effect on the depolarization time constant τ, implying that the depolarization was not arising from field inhomogeneities or the dipole-dipole interaction.

These experiments demonstrate the practicality and potential of using positive muons to probe magnetic materials. We are presently using smaller targets, even single crystals, to study the depolarization mechanism of rare earth metals such as dysprosium, erbium, gadolinium, and iron compounds such as Fe_3Si. We have observed muon precession in several of these materials and we are in the process of analyzing the data.

Thank you!

PION DECAY

BEFORE: $\left(\pi^+\right) \longrightarrow \vec{v}$

$\vec{c} \longleftarrow \left(\nu_\mu\right) \Rightarrow_{\vec{s}} \quad \overset{\vec{u}}{\underset{\vec{u}}{\rightleftarrows}} \left(\mu^+\right) \longrightarrow \vec{v}$

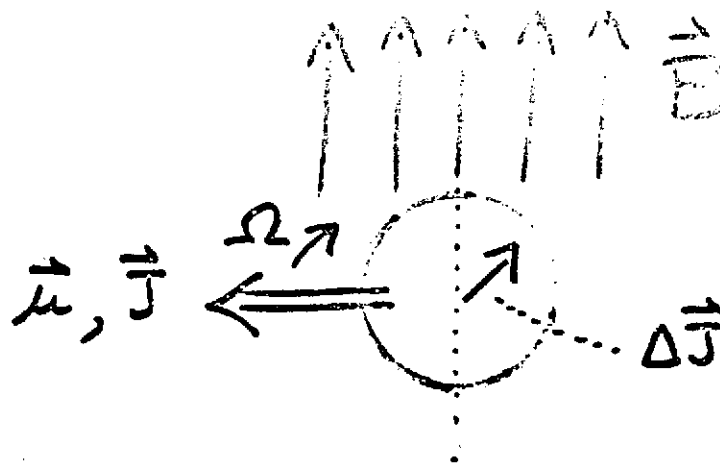$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
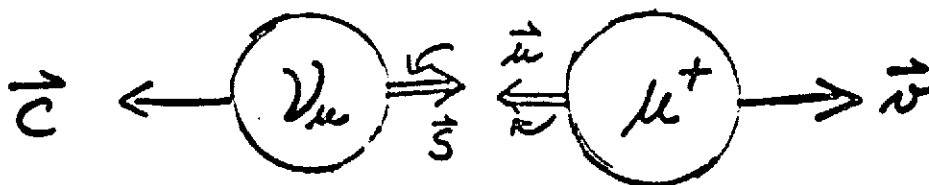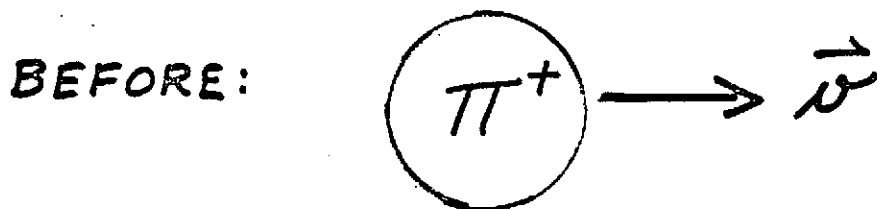
$$m_\pi \approx 273\, m_e$$

$$m_\mu \approx 207\, m_e$$

$$S_\pi = 0 \qquad S_\mu = \tfrac{1}{2}\hbar$$

PRECESSION OF MUON IN MAGNETIC FIELD

$$\frac{\Delta \vec{J}}{\Delta t} = \vec{\mu} \times \vec{B}$$

SIDE VIEW
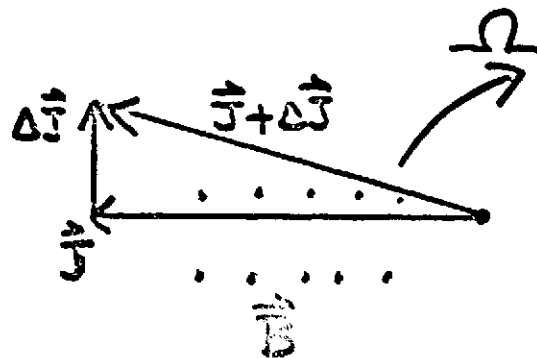
PRECESSION

TOP VIEW

Decay of Muon

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$
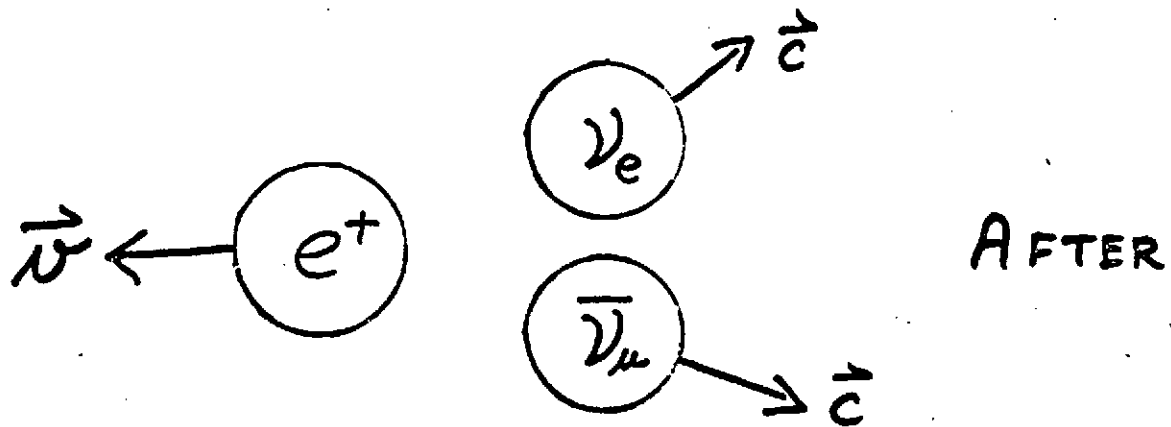
$$\vec{\mu}, \vec{J} \Longleftarrow \quad \boxed{\mu^+} \qquad \text{Before}$$

$$\tau_\mu = 2.2 \times 10^{-6} \text{ SEC.}$$

$$\nu_e \nearrow \vec{c}$$

$$\vec{\nu} \longleftarrow e^+ \qquad \text{After}$$

$$\overline{\nu}_\mu \searrow \vec{c}$$

THE POSITRON IS MOST LIKELY TO BE EMITTED IN THE DIRECTION OF THE MUON'S MAGNETIC MOMENT.
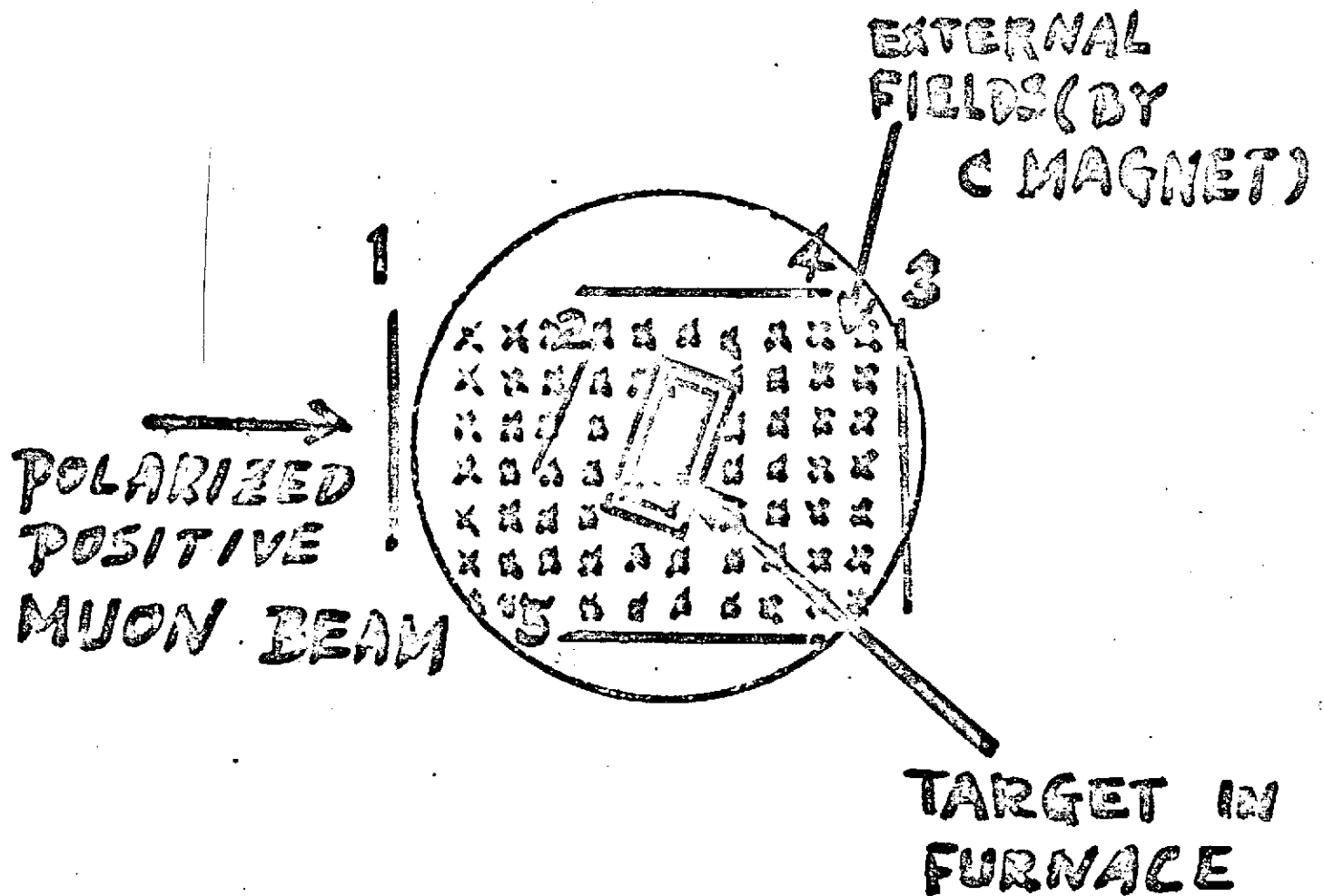
FIG. 1 SCHEMATIC OF MUON PRECESSION APPARATUS.
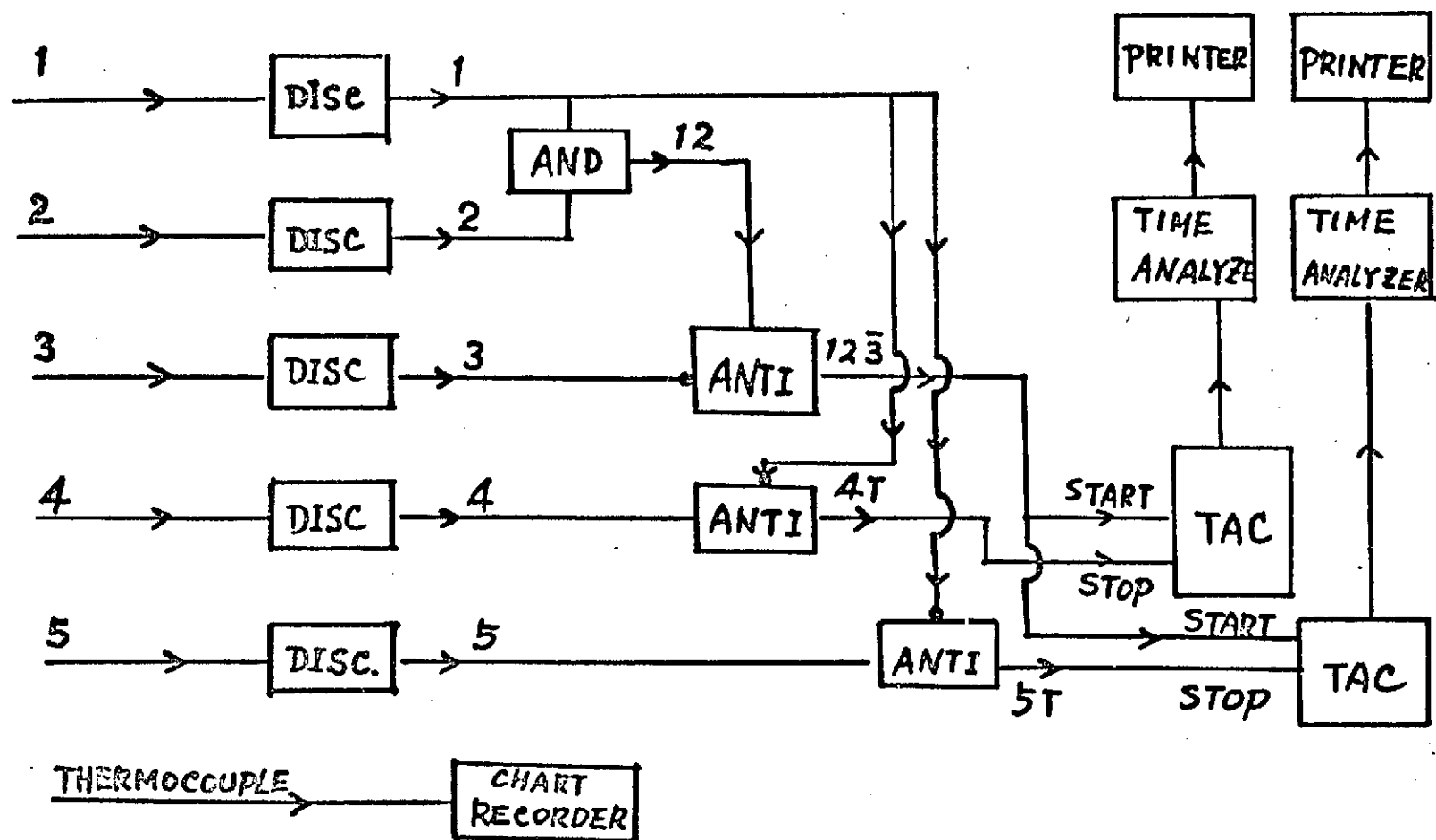
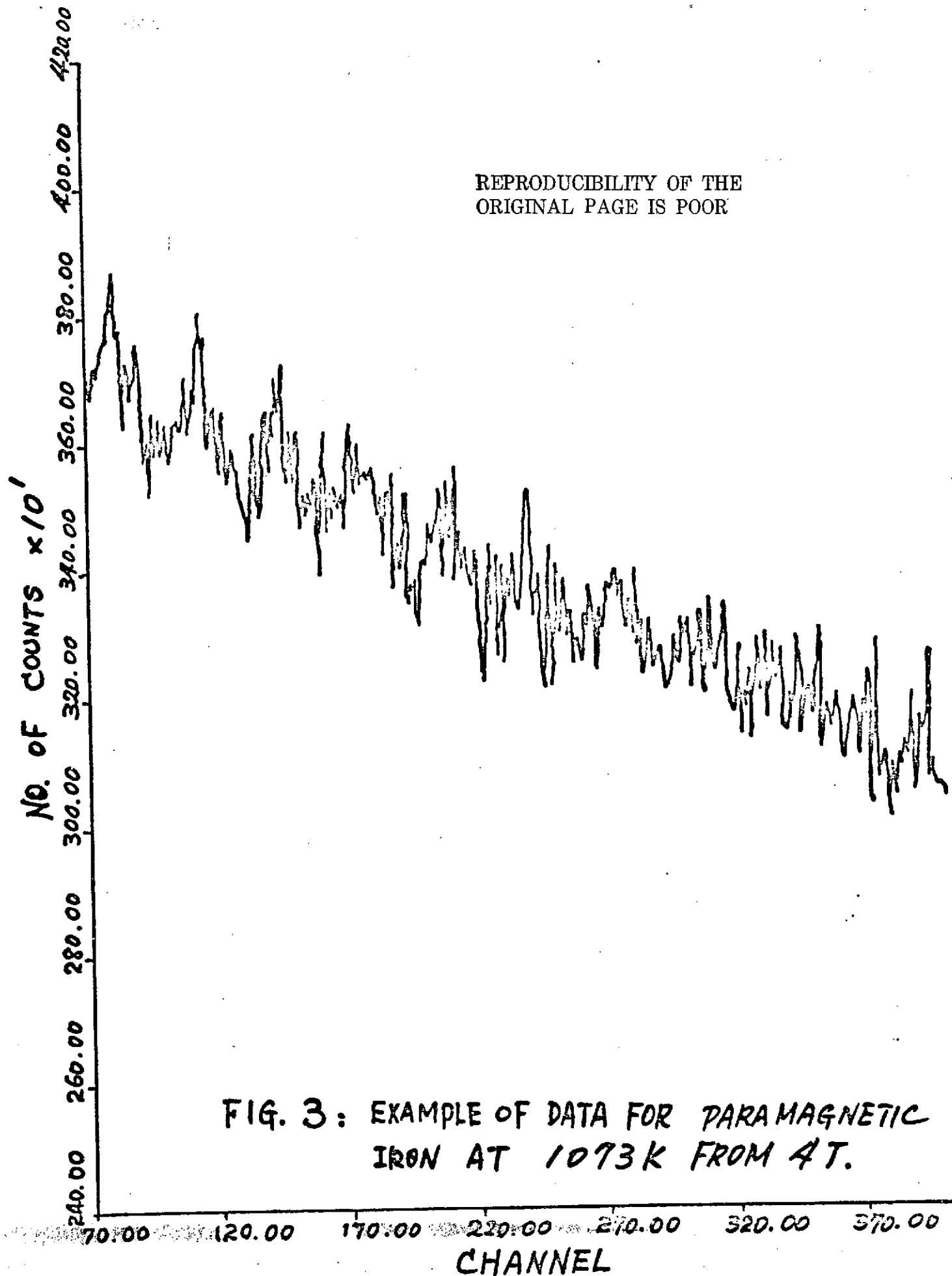FIG. 2: SCHEMATIC OF MUON PRECESSION ELECTRONICS

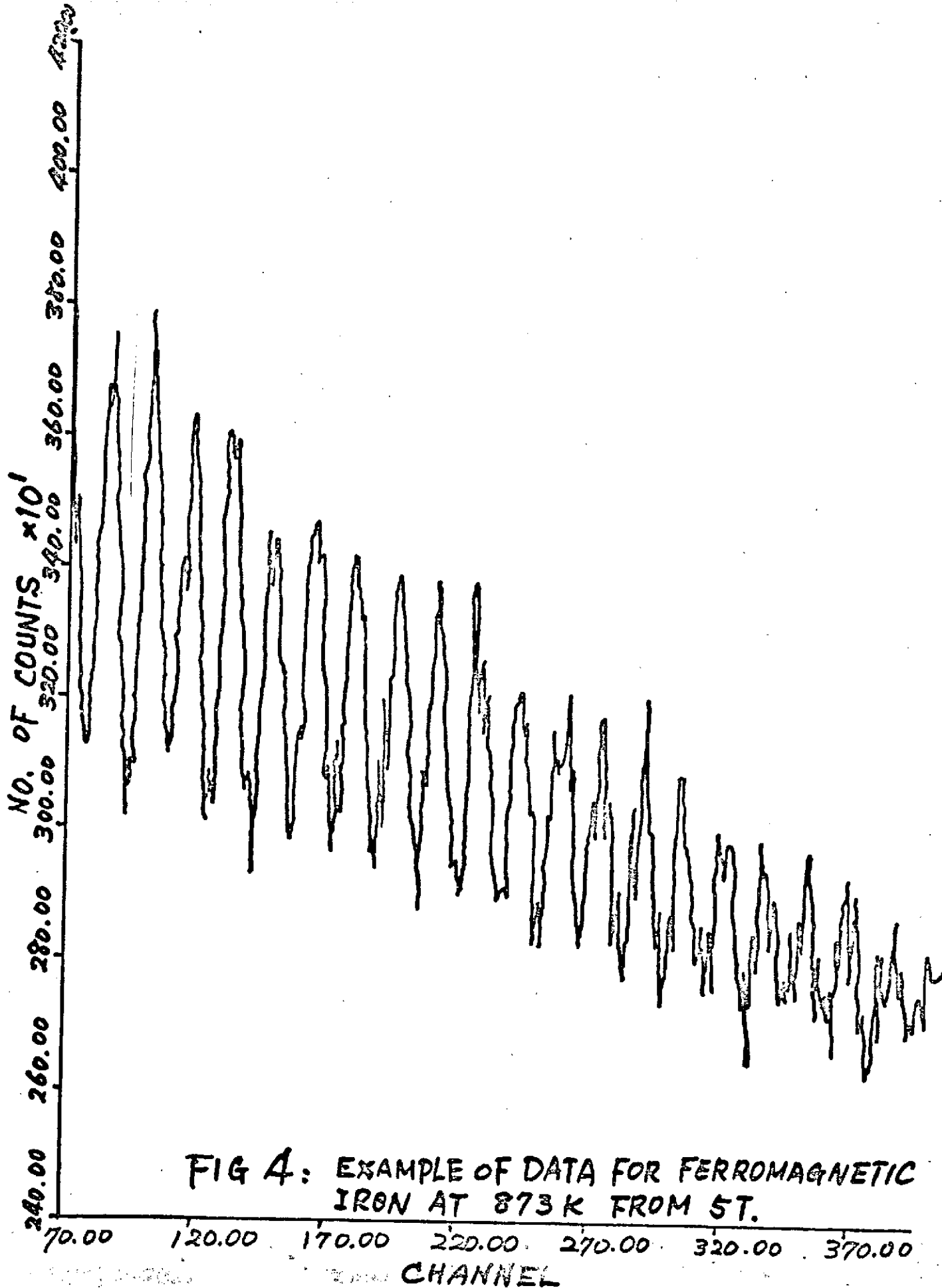FIG. 3: EXAMPLE OF DATA FOR PARAMAGNETIC IRON AT 1073K FROM 4T.

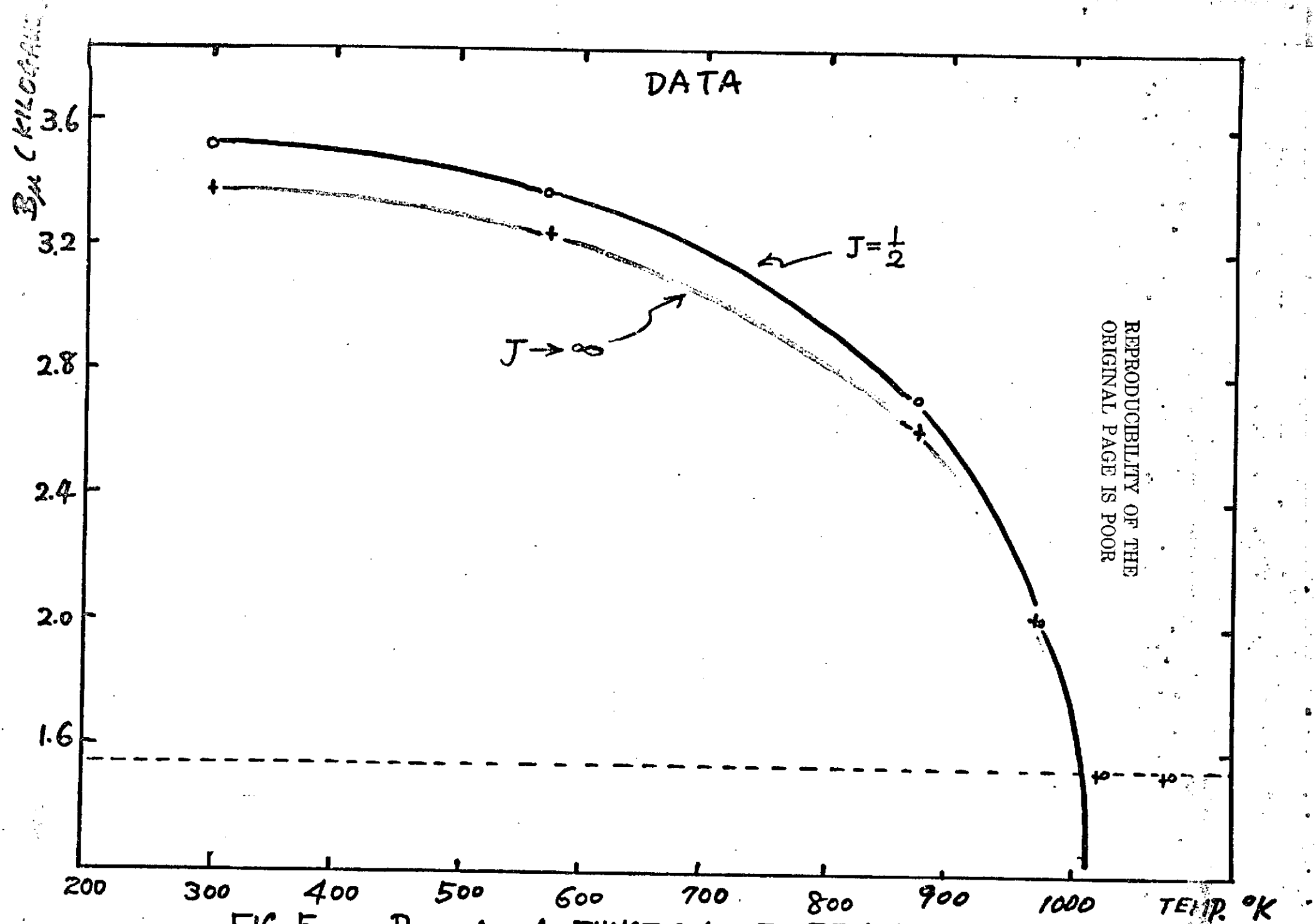FIG 4: EXAMPLE OF DATA FOR FERROMAGNETIC IRON AT 873 K FROM 5T.

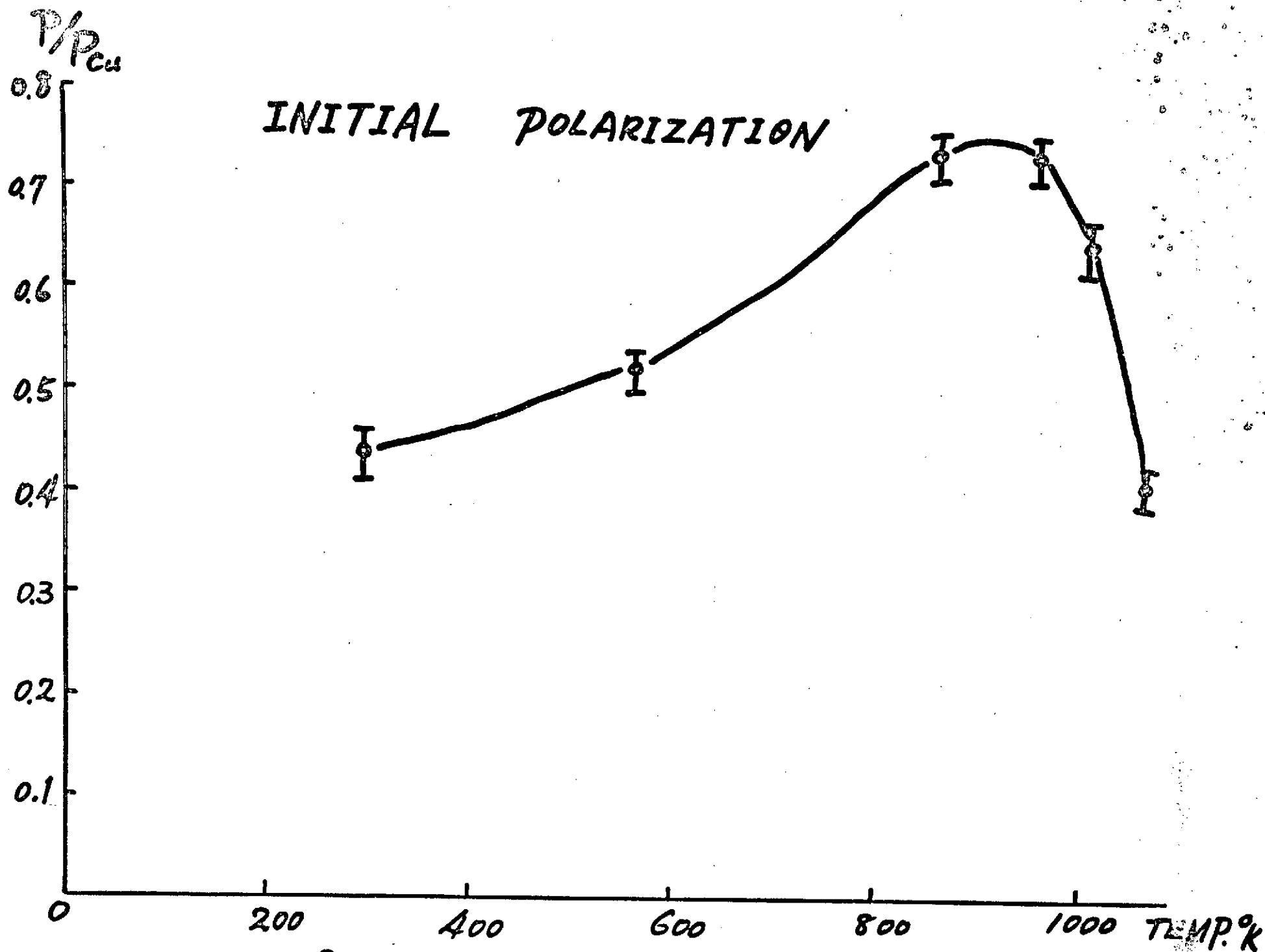FIG 5 : B$_\mu$ AS A FUNCTION OF TEMPERATURE.
DOT LINE IS THE EXTERNAL FIELD.

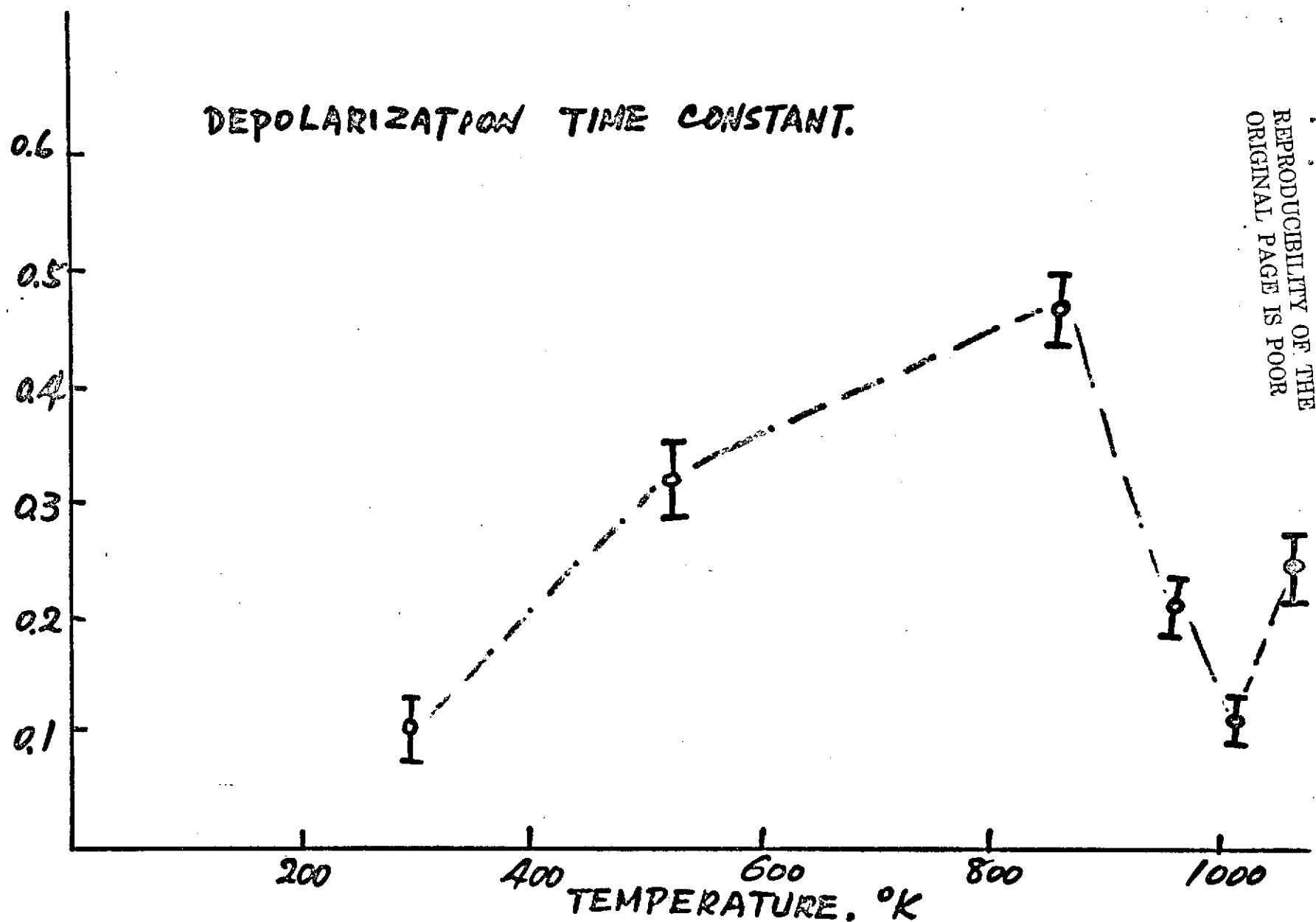FIG. 8: INITIAL POLARIZATION P/P_{cu} AS FUNCTION OF
TEMPERATURE

FIG. 9: DEPOLARIZATION TIME CONSTANT τ_γ AS FUNCTION OF TEMPERATURE.

$$N(t) = N_0 e^{-\lambda t}\left[1 + \alpha P e^{-t/\tau_r} \cos(\omega t + \phi)\right] + \text{Background} \quad (1$$

$$\omega = 2\mu_a B_\mu \hbar \quad \cdots\cdots\cdots\cdots\cdots (2)$$

TABLE 1: B_μ, τ_r, P WITH ERROR BARS

RUN		T,°K	B_μ, Gauss	τ_r, $\times 10^{-6}$ sec	P, 10^{-3}
O	4T	298	577.2? ± 18.82	0.097±0.016	63.10±7.20
	5T		3542.65±12.08	0.119±0.015	96.50±8.34
P	4T	573	3277.01±2.11	0.340±0.020	87.18±3.42
	5T		3272.3?±2.04	0.339±0.020	107.20±4.08
A	4T	873	2536.94±1.10	0.482±0.022	121.00±3.43
	5T		2547.96±1.10	0.467±0.020	144.90±3.99
B	4T	973	2097.73±2.79	0.274±0.015	107.40±4.48
	5T		2095.44±3.28	0.204±0.012	159.30±6.35
C	4T	1023	1414.50±12.17	0.104±0.012	90.00±7.46
	5T		1551.60±6.65	0.132±0.010	141.30±6.95
D	4T	1073	1526.15±7.16	0.173±0.021	62.99±5.01
	5T		1535.70±3.24	0.313±0.027	82.22±11.77